# NEWS

## Satellite Altimetry and the Intensification of Hurricane Katrina

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Remotely sensed infrared images of Hurricane Katrina taken on 26, 27, and 28 August 2005 (Figure 1, left panels) show the aerial extent of the cloud cover and the central "eye" increasing as the storm that swamped areas of the U.S. Gulf Coast intensified. Computer animations of such image sequences show forecasters the tracks of storms and are a familiar staple of weather news. Less well known is the role that satellite altimetry plays both in forecasting conditions that can intensify a tropical storm and in observing the storm conditions at the sea surface.

Satellite altimeter data indicate that Katrina intensified over areas of anomalously high dynamic topography rather than areas of unusually warm surface waters. Altimeter data from Katrina also for the first time observed the building of a storm surge.

Radar altimeters on board several satellites measure wind speed, wave height, and sea level over small (2 to 5 km radius) overlapping patches sampled at a sequence of points along each satellite's ground track. The altimeters use Ku-band radar that penetrates clouds and most rain, so that the data are available in nearly all weather conditions. Profiles of measured wind speed, wave height, and sea level along tracks passing through Katrina show the intensification of winds and waves associated with the growth of the storm and the wind-driven storm surge that hit the Gulf Coast (Figure 1, right panels).

Significant wave height (SWH) is defined as the peak-to-trough height of the largest third of the waves. Wave heights are largest at the point where each satellite track makes its closest approach to the eye of the storm, and they decrease symmetrically away from that point; the peak value of five m on 26 August had increased to 10 m on 27 August.

Near-surface wind speed is inferred from the power returned to the satellite after the scattering of the radar signal at the ocean surface. The wind speed profiles show a slightly asymmetric distribution with maxima slightly south of the wave height maxima, and increasing from 17 to 25 m/s over the three days shown.

The sea level measured by an altimeter is the combined effect of geoid undulations, tides, the ocean's response to meteorological forcing, and the dynamic ocean topography associated with currents in geostrophic balance. The rightmost panels of Figure 1 show the residual sea level anomaly after removing the geoidal, tidal, and geostrophic signals as well as an inverse barometer response to atmospheric pressure changes. The bottom rightmost panel, from the Geosat Follow-On (GFO) altimeter, shows sea level windward of the eye rising toward the shoreline and reaching 90 cm at the coast. This apparently is the wind-driven storm surge. To the authors' knowledge, this is the first observation of a storm surge by altimetry.

Popular press accounts [e.g., *Kolbert*, 2005; *Kristoff*, 2005] suggest that warm ocean surface waters intensified Katrina, but sea surface temperatures were around 30°C almost everywhere along Katrina's path through the ocean (Figure 2a). If intensification was driven predominantly by sea surface temperature, Katrina would have strengthened gradually over time.

Instead, Katrina intensified most rapidly when she was over areas of anomalously high dynamic topography, as measured by altimeters (Figure 2b). Katrina intensified first over a warm-core eddy east of Florida as she grew from a tropical depression to a Category 1 hurricane. Then, over the Loop Current and a warm-core ring in the Gulf of Mexico, she intensified from Category 1 to Category 5.

These dynamic topography highs are a proxy for the vertically integrated heat content within the water column. The depth of the warm water pool, and not merely the temperature at the surface, provides the reservoir of energy to intensify a storm [*Shay et al.*, 2000]. Later, Hurricane Rita also intensified to Category 5 over the same deep warm pool in the Gulf. However, Rita weakened afterwards when passing over an area of low dynamic topography near the Texas coast.

Since the dynamic topography changes only slowly over weeks, altimeter data collected long in advance of a hurricane can be used to forecast the potential for intensification [*Goni and Trinanes*, 2005].

The observed increase in intensity of hurricanes over the last decades has been correlated with increasing sea surface temperatures [*Emanuel*, 2005; *Trenberth*, 2005]. The example from Katrina suggests that any increase in hurricane intensity may be more directly correlated with variations in the thickness of the warm layer.

*Acknowledgments*

Radar altimeter data are from the NASA/Centre Nationale d'Études Spatiales TOPEX and Jason 1 altimeters, the European Space Agency ERS-2 and Envisat altimeters, and

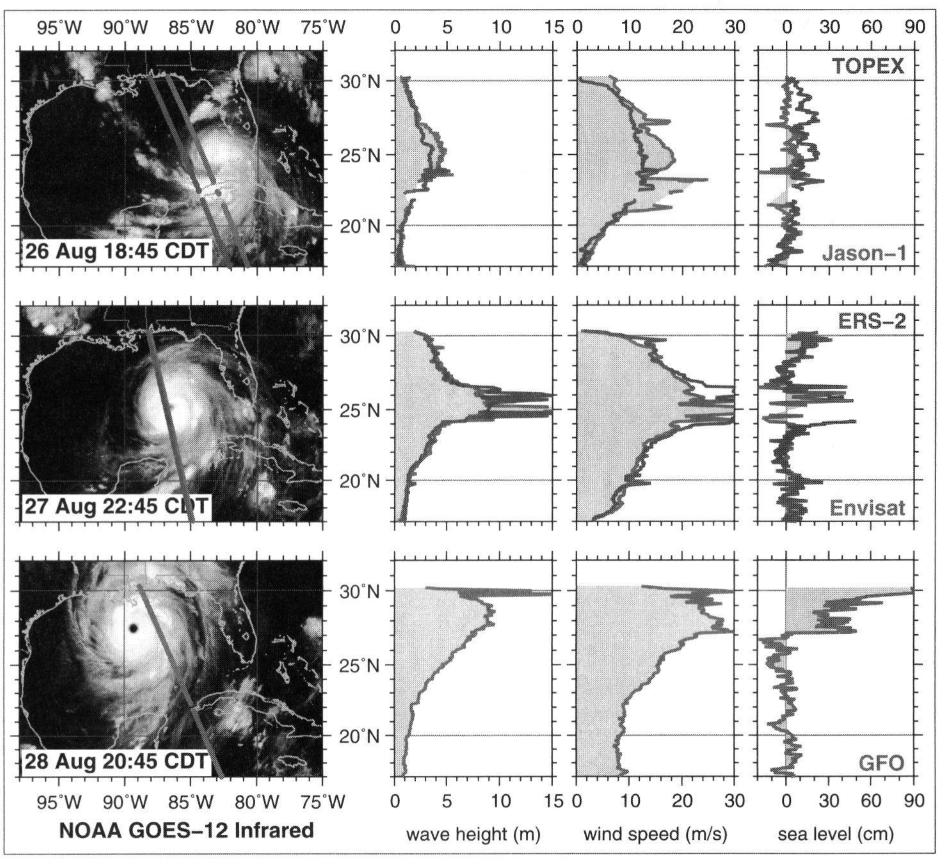


*Fig. 1. The left column shows a comparison of GOES 12 infrared images and altimeter data collected by (top) Jason 1 and TOPEX, (middle) Envisat and ERS-2, and (bottom) GFO during near-coincident overflights of Hurricane Katrina on 26, 27, and 28 August 2005. The images were taken within 20 minutes of the altimeter passes. The three columns on the right show the altimeter measurements of wave height, wind speed, and sea level anomaly, respectively, as a function of latitude along the altimeter tracks shown on the infrared images. Original color image appears at the back of this volume.*

the U.S. Navy GFO altimeter. Data were assimilated and analyzed through the Radar Altimeter Database System (RADS). The U.S. National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellite GOES 12 provided the infrared images of clouds, and the infrared sensors on NOAA Polar Operational Environmental Satellites (POES) were used to construct the sea surface temperature field. Thanks to Eelco Doornbos (Delft University of Technology, The Netherlands) for computing ERS-2 orbits. Remko Scharroo was supported by NASA grant NRA-03-OES-05. The views expressed here are solely the opinions of the authors and do not constitute a statement of policy, decision, or position on behalf of NOAA or the U.S. Government.

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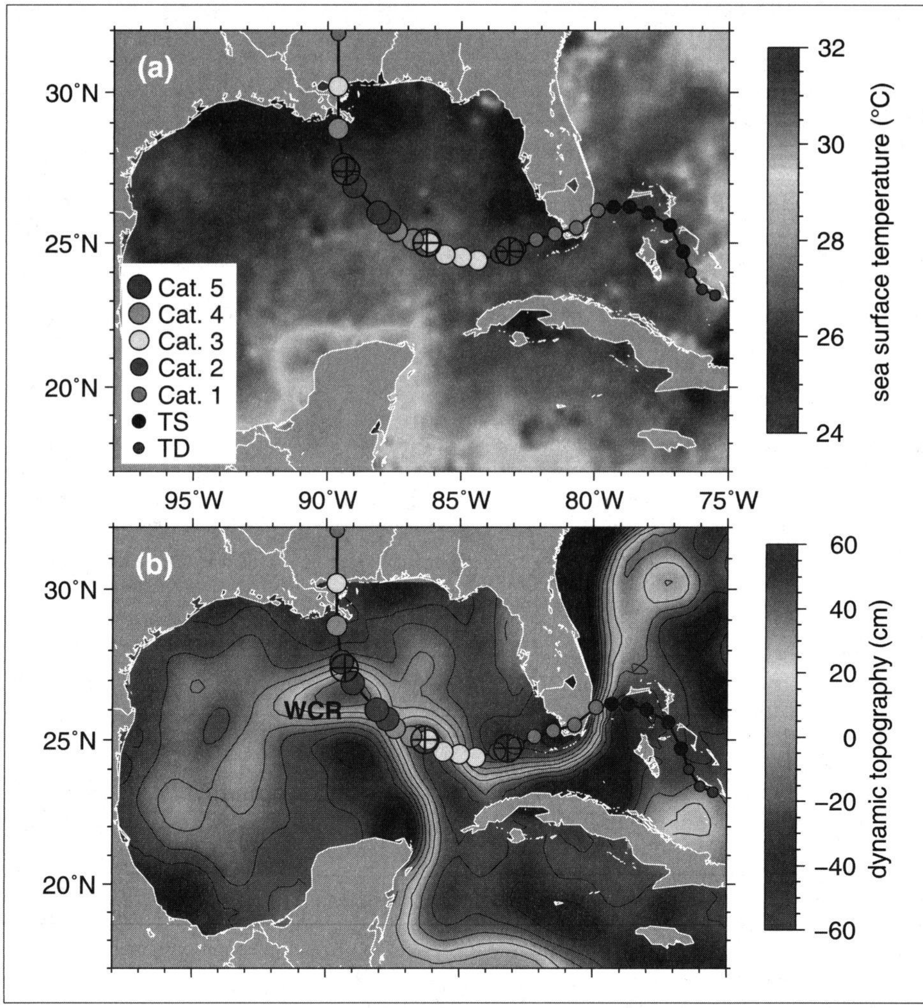


*Fig. 2. The location and intensity of Katrina at intervals of six hours (circles indicate data from National Hurricane Center advisories) show two intensification events. (a) Intensification is not correlated with sea surface temperature (from POES high-resolution infrared data). (b) In contrast, the intensifications correlate well with highs in the ocean dynamic topography (from Jason 1, TOPEX, Envisat, and GFO sea surface height data). The Loop Current can be seen entering the Gulf south of Cuba and exiting south of Florida; the warm-core ring (WCR) is the prominent high shedding from the Loop Current in the center of the Gulf. The crosshair symbols on the storm tracks show the storm position at the times of the three rows of panels in Figure 1. Original color image appears at the back of this volume.*

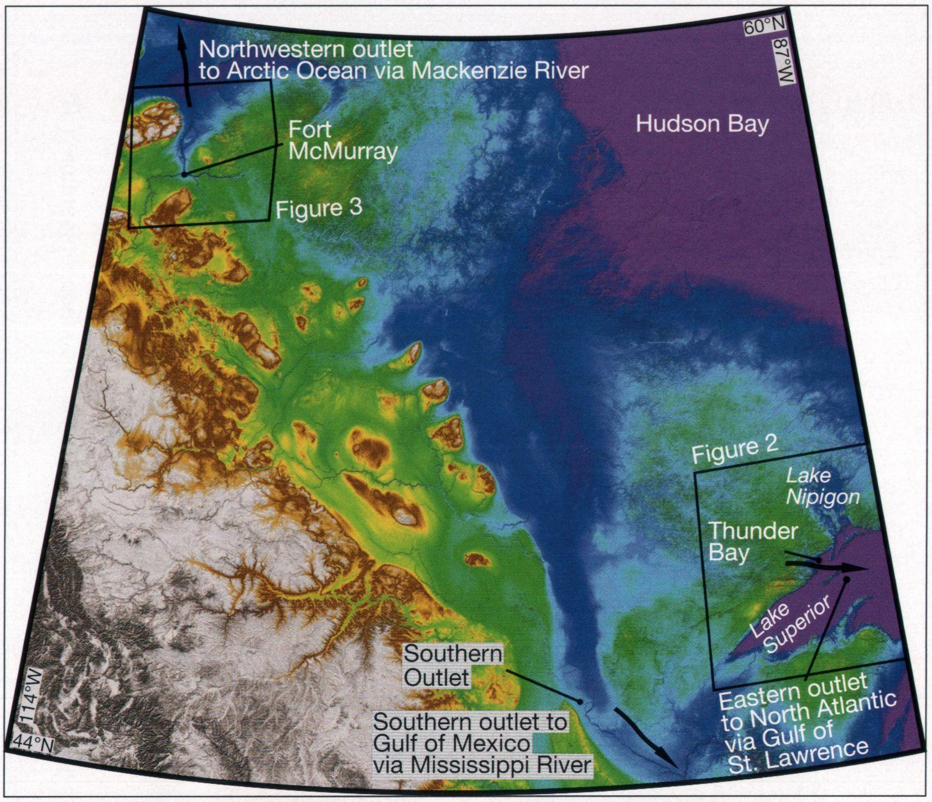


*Fig. 1. Digital elevation model of central North America showing the southern, eastern, and northwestern outlets of Lake Agassiz.*

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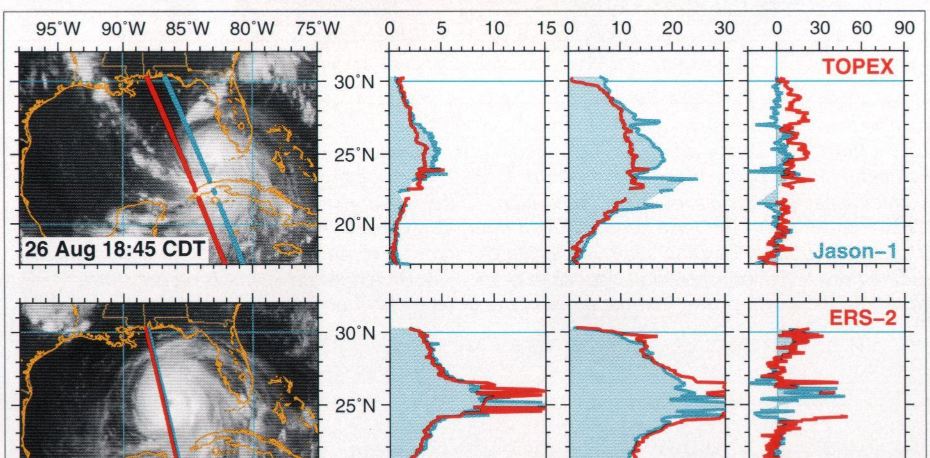


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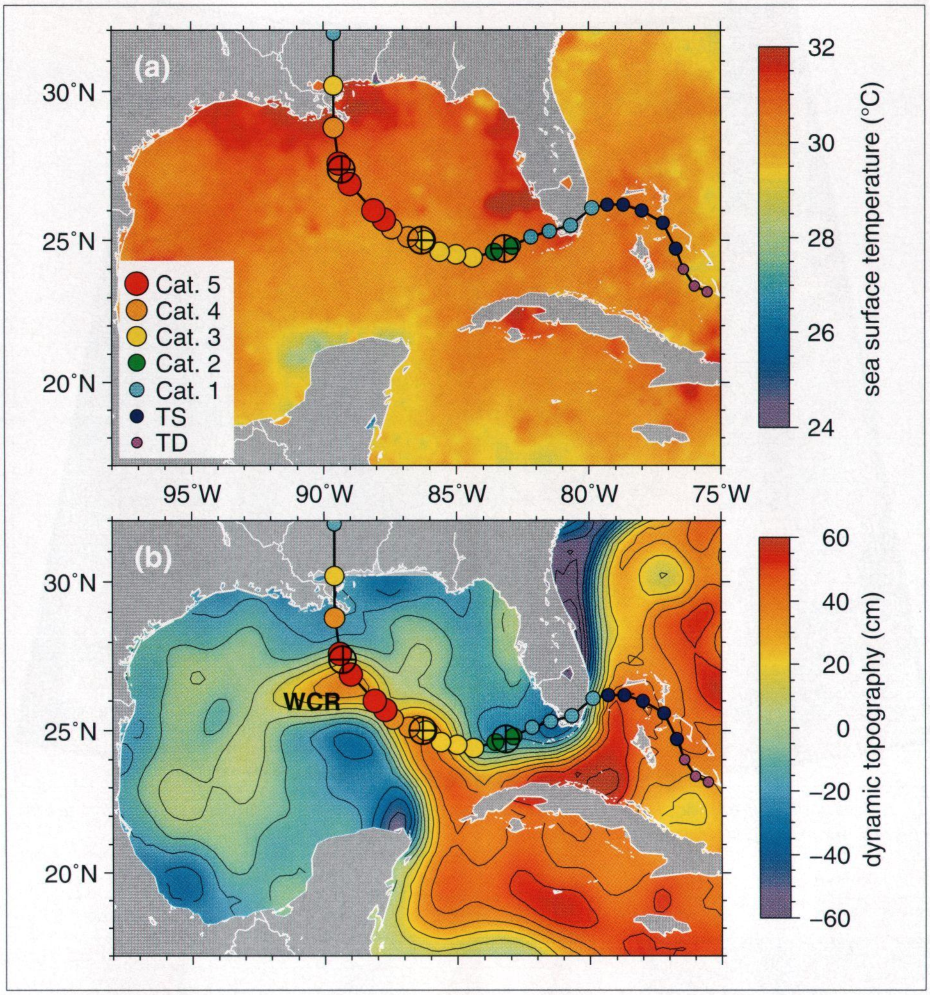


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